MINISTRY OF TRANSPORT

RAILWAY ACCIDENTS

Second interim report on the Accidents and Failures which occurred in Multiple Unit Electric Trains in the Scottish Region and Eastern Region British Railways

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MINISTRY OF TRANSPORT,
ST. CHRISTOPHER HOUSE,
SOUTHWARK STREET,
LONDON, S.E.1.
30th May, 1961.

SIR,

I have the honour to present for the information of the Minister of Transport, in accordance with the Order dated 20th December, 1960, a second interim report on my Inquiries into the accidents which occurred on 13th and 17th December, 1960, in multiple-unit trains on the Glasgow suburban electric service in the Scottish Region, and on my investigations into all other relevant accidents, failures and troubles experienced in the operation of these services and of those on the other high voltage A.C. overhead electrification systems of British Railways.

2. In view of the public concern over the withdrawal of the electric trains from the Glasgow suburban service I prepared an interim report dated 13th January, 1961. In it I gave the results of the investigations which led to the establishment of the primary cause of those failures and announced the action that was being taken to get the electric services re-started.

3. Since then my investigations have been concerned primarily with the failures of electrical equipment in some of the multiple-unit trains running on the Eastern Region's recently electrified lines to see whether they were in any way interrelated to those in the Scottish Region.

The failure of traction motors and rectifiers installed by the General Electric Company in multiple-unit trains running on the North East London suburban routes to and from Liverpool Street were so serious that a number of trains had been withdrawn early in December, 1960, and on 12th December the electric services on some of these routes were reduced. A number of modifications were made to the electrical equipment and it was hoped that these would prove effective, but failures continued to occur and it was decided to introduce a further series of modifications.

4. On 6th January, 1961, following discussions between Mr. J. Ratter, a member of the British Transport Commission, and myself, Mr. E. L. E. Wheatcroft, M.A., M.I.Mech.E., M.I.E.E., a partner of Messrs. Merz and McLellan and a member of the British Transport Commission's panel of consulting engineers, was requested by the Commission to investigate the causes of these failures. Since then intensive investigations have been carried out by the Commission's and the Eastern Region's electrical engineers, by Mr. Wheatcroft and Mr. T. W. Wilcox, M.I.E.E., another partner of Messrs. Merz and McLellan, and by the engineers and staff of the General Electric Company.

5. As stated in my first interim report, Mr. F. J. Lane, O.B.E., M.Sc., M.I.E.E., a partner of Messrs. Preece, Cardew and Rider, and another member of the Commission's panel of consulting engineers, has been making an investigation into the failures of the Glasgow multiple-unit trains and all matters relevant to them. He has been collaborating closely with Mr. Wheatcroft so as to ensure that all aspects of the subjects under review are fully covered. They have been giving me every assistance in my Inquiries.

6. As a result of the joint consultations and investigations, including theoretical analyses, laboratory tests, measurements of equipment in service and the running of a complete train equipped as a mobile laboratory, the primary

causes of the failures of the G.E.C. traction motor equipment have now been found and urgent action has been taken to provide a cure.

These serious failures coupled with those in the Scottish Region have thrown some suspicion on the reliability of British traction equipment and therefore I have considered it essential to report with the minimum of delay the result of these further investigations and of the action taken to get all the G.E.C. stock into service again. The troubles with the other electrified stock on the Eastern Region have not been serious but they will be discussed in my final report.

7. I have added a section about the progress made to date in the modification and testing of the Glasgow suburban electric stock.

8. Investigations into the way in which the failures on all electrified services may be interrelated are not yet complete, but this aspect of the problem together with my remarks and recommendations on all relevant matters will be included in my final report.

9. This report is divided into the following sections :—

- I. Description of the North East London suburban electrified lines in the Eastern Region.
- II. Description of the Eastern Region multiple-unit stock, fitted with G.E.C. electrical equipment (the G.E.C. units).
- III. Review of the running of the G.E.C. units and of the troubles experienced with them.
- IV. Notes on the technical investigations and the action taken to rectify the defects in the G.E.C. units.
- V. Description of the G.E.C. test train and of the results achieved with it.
- VI. Messrs. Merz and McLellan's interim statement.
- VII. Note on the progress made in the modification and testing of the Glasgow suburban electric stock.
- VIII. Conclusion and Remarks.

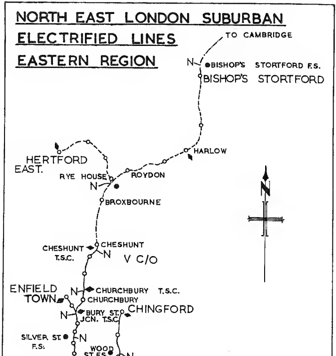
I. The North East London Suburban Electrified Lines

The extent of the system

10. This comprehensive suburban electrification which is illustrated by the accompanying map comprises the lines from Liverpool Street to Bishop's Stortford, via Bethnal Green and the Churchbury Loop, with branches from Hackney Downs to Chingford, Bury Street Junction to Enfield Town, and Broxbourne Junction to Hertford East. The main line and the branches are all two-track, apart from the section from Bethnal Green to Hackney Downs which is four-track, and from Liverpool Street to Bethnal Green which is six-track and includes those lines carrying the main line steam and diesel trains to and from Liverpool Street and the electric trains on the Liverpool Street-Shenfield-Southend (Victoria) service.

11. The overhead conductors from Liverpool Street to Cheshunt on the Bishop's Stortford main line and on the Chingford and Enfield branches are energised at 6.25 kV ; those on the main line from Cheshunt to Bishop's Stortford and on the Hertford East branch are energised at 25 kV. The total route mileage is 46 miles, of which 23.5 are electrified at 6.25 kV and the remainder at 25 kV. These routes comprise 111 single track miles, of which 58 are at 6.25 kV and 53 at 25 kV.

The only voltage changeover point on the system is at Cheshunt.



LINES ELECTRIFIED AT 6·25 KV. ————

LINES ELECTRIFIED AT 25 KV. -------

PROJECTED LINES —·—·—

PASSENGER STN................o

FEEDER STATION................●

TRACK SECTIONING CABIN............♦

NEUTRAL SECTION..........N

VOLTAGE CHANGE-OVER POINT..........V C/O

The power supply

12. Power for the system is supplied at the following points :—

(*a*) Bethnal Green : where electrical energy at 6.25 kV is fed to the track sections Liverpool Street-Bethnal Green : Bethnal Green-Stoke Newington—Clapton : and Bethnal Green-Bow Junction (on the Shenfield line).

(*b*) Silver Street : where electrical energy at 6.25 kV is fed to the section between Stoke Newington and Churchbury and to the Enfield branch.

(*c*) Wood Street : where feeders at 6.25 kV supply energy to the section between Clapton and Chingford.

(*d*) Rye House : where electrical energy at 25 kV is supplied to the section between Cheshunt and Bishop's Stortford, to the Hertford East branch and to a stepdown transformer at Cheshunt which supplies electrical energy at 6.25 kV to the section between Cheshunt and Churchbury.

(*e*) Bishop's Stortford : which at present is only an emergency feeding point available to supply energy at 25 kV to the main line and to the Hertford East branch in the event of a breakdown of the Rye House supply. Bishop's Stortford will become a Track Sectioning Cabin should the electrification be extended to Cambridge.

13. Track Sectioning Cabins on the 6.25 kV sections are provided at Liverpool Street, Hackney Downs, Clapton, Stoke Newington, Bury Street Junction, Churchbury, Chingford, Enfield and Cheshunt. On the 25 kV section there are Track Sectioning Cabins at Harlow and Cheshunt on the main line to Bishop's Stortford and at Hertford East.

14. High speed oil-immersed circuit-breakers are provided at all feeder points and Track Sectioning Cabins. On the 6.25 kV system they are rated at 100 M.V.A. at Track Sectioning Cabins, and at 150 M.V.A. at feeding points. On the 25 kV system the track feeder circuit-breakers at Harlow, Bishop's Stortford and Hertford East are rated at 150 M.V.A., and at Rye House and at the feeding points they are rated at 300 M.V.A.

All the track feeder circuit-breakers are provided with automatic re-closing relays, but so far this feature has not been put into service.

The system is controlled by supervisory remote control from the new Romford Electrical Control Station, on the Shenfield line.

Overhead equipment

15. The overhead equipment is mainly of three types : from Liverpool Street to Bethnal Green it is 0.75 sq. in. compound catenary without weight tensioning, matching the equipment installed for the original 1,500 volts D.C. electrification of the adjacent tracks. From Bethnal Green outwards to Stoke Newington and Clapton where speed restrictions of 25 to 40 m.p.h. are in force it is 0.25 sq. in. simple catenary fixed equipment. Further out on the country side this equipment is automatically tensioned by applied weights as higher speeds up to 60 m.p.h. are permitted. From Bury Street Junction outwards where still higher speeds up to 75 m.p.h. are allowed, stitched catenary with weight tensioning is used.

Neutral sections

16. In order to avoid paralleling two different phases of the power supply, neutral sections are installed at those feeder stations and Track Sectioning Cabins where different phases may be fed to adjoining lengths of the overhead lines. They are also installed at points where there is a change of voltage. These neutral sections comprise three parts so arranged that one of the three is never made alive by the passage of the pantograph. These neutral sections have switches so that they can be made alive if the sectioning of the line is not required at that point of the system at any particular time.

The neutral sections are provided with ground magnets spaced suitably in advance and in the rear of them. These magnets operate the voltage selection equipment on the train, as described in paragraph 38. The first magnet causes the train circuit-breaker to open while the train is passing through the neutral section to prevent drawing a power arc from the live part of the system to the neutral part, and the second magnet causes the circuit-breaker to re-close automatically when the train leaves the neutral section.

The track magnets are placed on the sleeper ends outside the running rails, the first one 85 feet before the entrance to the neutral section when the maximum allowable speed is 75 m.p.h. (the distance varies according to the speed, i.e. 75 feet for 60 and 100 feet for 100 m.p.h.), and the second magnet is placed 60 feet beyond the exit.

The neutral section at the voltage changeover point is now fitted with a condenser to ensure that it is maintained close to earth potential.

17. The neutral sections are at Bethnal Green, Clapton, Wood Street, Stoke Newington, Silver Street, Churchbury and Rye House and at the voltage changeover point at Cheshunt.

Service characteristics

18. Conditions on the N.E. London suburban lines differ widely. Those on the Chingford and Enfield lines, especially the latter, are severe. These lines have sharp curvature and steep gradients (the minimum curvature is 7.6 chains and the maximum gradient is 1 in 77) and the distances between stations are short ; the average is only one mile. All the overhead conductors are charged at 6.25 kV and there are five neutral sections where the circuit-breakers on the motor coaches are automatically opened and re-closed.

The services to Hertford East and Bishop's Stortford are run at higher speeds with less frequent stops ; the distances apart of stopping stations average 1.8 miles on the Hertford East branch and 2.2 miles on the Bishop's Stortford main line. Curvature and gradients also are not so severe (the minimum curvature is 12 chains and the maximum gradient is 1 in 95). More than half the route is charged at 25 kV and all trains pass through the changeover section at Cheshunt as well as through four neutral sections on the 6.25 kV system.

Train services

19. With the introduction of the electric timings on 21st November 1960, the services were greatly intensified and speeds were increased ; the maximum was raised to 75 m.p.h. The peak and off-peak traffic averaged the following numbers of Up and Down trains per hour :—

	Peak Up and Down			Off-Peak Up and Down			
	Trains	Units per Trains	Cars per Unit	Trains	Units per Trains	Cars per Unit	Average speed m.p.h. (incl. stops)
To Chingford	9	3	3	6	3	3	27
To Enfield..	6	2	3	6	2	3	22
To Hertford East.. ..	3*	1	4	2*	1	4	29
To Bishop's Stortford ..	3*	1	4	2*	1	4	33
Total between Liverpool Street and Hackney Downs	18	—	—	14	—	—	

(*) These trains run coupled together between Liverpool Street and Broxbourne, where they are split on the Down journey and coupled together again on the returning Up journey.

20. Owing to the failure of many G.E.C. units the services were reduced on 12th December, 1960. On the Chingford line the morning peak service was reduced to 6 trains per hour and in the evening peak the full services were maintained, but with trains of 6 cars instead of 9. The off-peak service was also maintained with 6-car trains. The Enfield peak service was reduced to 3 trains per hour but 4-car units were substituted for 3-car units. The off-peak service was maintained with single 4-car units. Some adjustments have been made since then but the full service has not yet been restored.

These results have been achieved largely by using stock destined for the London, Tilbury and Southend line.

II. The G.E.C. Units

21. The G.E.C. fleet comprises 52 3-car units and 19 4-car units. The coaches were built at the British Railways' Doncaster and York Works and the electrical equipment was supplied by the G.E.C. They were designed to operate on the N.E. London suburban lines in accordance with the specifications laid down by the Chief Electrical Engineer of the British Transport Commission. Brief descriptions of the electrical equipment as originally supplied by the G.E.C. are given in the paragraphs which follow.

Composition of the units

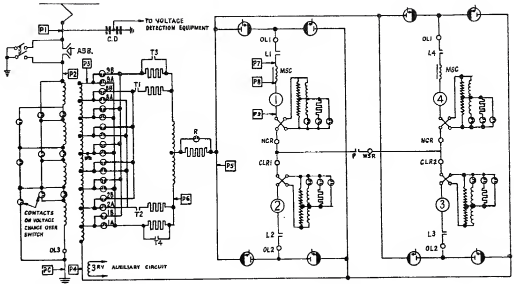
22. The 3-car unit comprises driving trailers at the ends with a motor coach in the middle. A composite non-driving trailer is added to make up a 4-car unit.

The motor coach is powered by four motors, one on each axle, and it carries the pantograph mounted above the guard's van. The power equipment is carried below the floor of the coach but the low tension (LT) switchgear and some other auxiliary equipment is in a compartment between the guard's van and the passenger compartment. The driving trailers have a cab at one end, and one of them carries the battery with its charging equipment and the air compressor for charging the braking system.

Power circuits

23. The schematic diagram on page 8 shows the main power circuits. The current from the overhead conductor is collected by the pantograph and after passing through an air-blast circuit-breaker (A.B.B.) on the roof, it is carried through a heavily insulated cable to a voltage changeover switch which connects the four sections of the transformer primary winding in series for 25 kV operation or in parallel for 6.25 kV operation. The return current from the transformer is fed to the wheels through brushes on each axle of the motor coach.

The transformer secondary winding supplies current to two circuits, each feeding two traction motors in series through a group of four single anode mercury arc rectifiers.



G.E.C. UNIT. SCHEMATIC DIAGRAM OF MAIN POWER CIRCUITS

G. E. C. UNITS

KEY TO SYMBOLS ON THE SCHEMATIC DIAGRAM OF POWER CIRCUITS

1. C. D.	Capacitor divider
2. A. B.B.	Air blast circuit breaker
3. 1A. 1B. etc.	Tapping switch contacts
4. R.	Tapping switch contact
5. T1. T2. T3.& T4.	Tapping contactors
6. OL1. OL2. & OL3.	Over load relays
7. L1. L2. L3. & L4.	Motor contactors
8. M. S. C.	Motor smoothing choke
9. N. C. R.	No current relay
10. C. L.R. 1 & 2.	Current limit relays
11. P.	Motor paralleling contactor
12. W. S.R.	Wheel slip relay
13. $\boxed{\text{P1.}}$ to $\boxed{\text{P9.}}$	Voltage measurement points to earth on the test train
14. $\boxed{\text{PC.}}$	Primary current measurement point on the test train

24. The motor voltage is controlled by cam-operated tapping switches on the transformer secondary using two contacts per tap in conjunction with series resistances and a centre tapped choke. By these means 18 steps (1A to 9B) are provided by nine taps, and in addition there are running steps with no series resistance in circuit. Two further steps are provided by motor field weakening, of which the second is a running step. The earth connection in the motor circuit is at the mid-point of the transformer secondary.

An equalising connection is provided between the mid-points of each pair of motors so as to reduce the rise in voltage when a motor develops slip.

25. The current from the rectifiers is fed through smoothing chokes which are oil-cooled, air-gap reactors (M.S.C. on the diagram). They are designed to limit the A.C. ripple in the D.C. motor circuit to 30 per cent. at any current between half and twice the continuous rating.

So long as the pantograph remains in contact with the overhead conductor the rectifiers are connected to the secondary of the transformer through tapping switch contact 1A.

Control circuits

26. Movement of the master controller causes the tapping switch to progress step by step under the control of a current limit relay which regulates the lifting of the pawls. The tap changer in notching up then causes an increasing voltage to be applied to the traction motors.

The pantograph

27. The pantograph is of the same type as used on all British Railways' locomotives and multiple-units operating on the dual high voltage system. It is a British modification of a French design and is known as the Stone-Faiveley AM-BR type. It consists of a single air-operated spring controlled member on which is mounted a single pan with two rows of graphite current collectors. It is raised by admitting air to a motor which overcomes the holding down springs.

It is designed to operate with the overhead conductor heights varying from 13 ft. 5 ins. under low bridges, with a clearance of only 4 ins. between the conductor and the moving load, up to a maximum of 20 ft. above rail level; the standard height of the conductor is 16 ft. The pressure between the pantograph and the conductor varies between 18 and 20 lbs

The air-blast circuit-breaker

28. The Brown Boveri air-blast circuit-breaker (A.B.B.) with which the G.E.C. units are equipped has also been standardised throughout the A.C. fleet except on a number of locomotives and multiple-units equipped by A.E.I. (Manchester) who have recently developed one of somewhat similar type. The Brown Boveri breaker has been used successfully both at 15 kV and 25 kV, but its use on the G.E.C. and other British Railways' units is the first application of a single circuit-breaker to operate at dual voltages of either 25 kV or 6.25 kV.

The breaker comprises an arc extinction chamber and an isolating switch. In the arc extinction chamber there are two " blast " contacts normally closed and housed in a porcelain insulator with metal ends. One contact is fixed and the other opens at high speed against a spring when air pressure is applied as the result of the operation of a control or a protective relay in the breaker holding coil circuit. The power circuit is finally opened by an air-operated isolating switch forming part of the breaker, after which the " blast " contact

re-closes under spring pressure. The isolating switch is closed by energising the re-set coil which opens a valve to admit air to the closing side of this switch's operating piston.

The two terminals formed by the metal ends of the arc extinction chamber are shunted by a non-linear resistance to reduce switching over-voltage. The circuit-breaker is very rapid in its action and the primary over-voltages are governed by the combined characteristics of the circuit that is being opened and the shunting resistance. The maximum voltages are substantially the same whether operating on 25 kV or 6.25 kV.

The transformer

29. The transformer, which weighs about four tons, is mounted between the main members of the underframe in the centre of the vehicle. It has a rating of 1,000 kVA and, as already mentioned, it can take current through the primary winding either at 25 kV or 6.25 kV. The secondary winding has a rated voltage of 1,875 volts and there is a tertiary winding for the supply of auxiliaries at 270 volts.

The transformer is of two-limb design with the coil axes horizontal. The tertiary winding is wound next to each limb of the core, then the secondary in two layers, and finally the primary winding.

A cooling duct is provided between the tertiary and the secondary windings and between the layers of the secondary winding. In addition two ducts are provided between the primary and secondary windings, separated by the major insulation.

The transformer is cooled by forced oil circulation in a fan cooled radiator. The whole of the circulating system is under positive pressure, and variations in volume on account of changing temperatures are taken up in a conservator tank mounted in the equipment compartment in the guard's van.

The voltage changeover switch

30. This is of the "off-load" type and it is operated by relays which respond either to the 25 kV or to the 6.25 kV supply as explained in paragraph 39. It is a 9-pole oil filled switch with contactor-type elements operated by insulated links from a common shaft which is rotated to either of the two positions by an external air engine. The switch is flange-mounted on the transformer tank but it has a separate oil supply.

The tapping switch

31. This is an electro-pneumatic camshaft-operated switch with cam-opened and spring-closed contacts. In order to provide adequate mechanical spacing between the steps there are two camshafts (each with its own air engine) which, when operated for notching-up, move alternately under the control of a common escapement mechanism. The switch with its interlocks and air engine are mounted in a dustproof case alongside the transformer tank.

The rectifiers

32. The G.E.C. Com-Pak rectifiers, each nominally rated at 125 amps/750 volts, are of the mercury arc excitron type. They are contained in two cases mounted on the underframe of the coach. The larger case contains the eight rectifiers with their fan-cooled radiator and circulating cooling water system, the other case the ignition and excitation gear for the rectifiers.

33. Each rectifier comprises a vacuum tight metal cylinder of internal dimensions

about 6 ins. high × 6 ins. diameter, hermetically sealed. This cylinder contains a stainless steel main anode, insulated by a glass seal, and a cathode with means for preventing mercury swill and for maintaining a substantially constant level of mercury in the annular trough between the cathode pressing and the cylinder wall. The anode and cathode are liquid cooled in series.

The rectifier is ignited by a jet of mercury expelled upwards through a nozzle from a reservoir by a steel ball forced downwards by the magnetic field of an external solenoid. The jet impinges on a small graphite excitation anode in the vicinity of the cathode. This anode is energised with D.C. from an auxiliary excitation rectifier. The arc once struck is maintained independently of the current in the main anode.

Interposed between the cathode and the main anode is an arrangement of metal de-ionising grids at tank potential. A series of cooling coils is welded to the outside of the tank to ensure that the tank wall acts as a mercury vapour condensing surface.

34. The basic principle of operation of the Com-Pak rectifier is that the cathode spot anchors itself to the meniscus formed between the water-cooled cathode dome and the mercury in the annular trough ; this anchoring action prevents the arc freely traversing the surface of the mercury and avoids excessive evolution of mercury vapour and enables the water-cooled anode to be brought into close proximity to the cathode, giving a small arc drop and enabling the overall size of the rectifier to be reduced.

The traction motors

35. The 4-200 h.p. Class B insulated motors are axle-hung nose suspended and operate in series pairs. They are four-pole machines with interpoles. They have been designed to operate on a rectified supply of 693 volts per motor with a continuously rated current of 220 amps. with full field and 240 amps. with weak field. They have been designed to operate with the A.C. ripple mentioned in paragraph 25. The methods of control have already been described in paragraph 26.

The motorman's controls

36. These are similar to those on the other A.C. multiple units and comprise a master controller with a main handle incorporating the dead man's feature and a reversing handle. A separate combined brake controller operates the electro-pneumatic and Westinghouse air brakes.

The master controller has four notches in addition to the " off " position. They are :—

1. Shunt.
2. Half Voltage.
3. Full Voltage.
4. Weak Field.

37. A lamp indicator in the motorman's cab is illuminated whenever the pantograph is in contact with an energised overhead conductor. The fault indicator lamp, however, is in the guard's van.

The motorman and guard can communicate with each other by means of the " loudaphone " system, or by a series of code rings on the train bell system.

The voltage selection equipment

38. As already explained, the 25 kV and the 6.25 kV sections of the overhead equipment are separated by a neutral section, and the changeover from one voltage to another is initiated by permanent magnet inductors.

Each motor coach carries a receiver mounted on a bogie and operated by the magnetic field of the ground magnets. The receiver is a polarised latched relay fitted with a re-set coil. On passing over the first inductor the receiver operates a relay which opens the air-blast circuit-breaker before the pantograph reaches the dead section, and on passing over the second inductor the receiver operates another relay which releases the lock on the circuit-breaker so that it can be closed by the voltage selection equipment.

39. The voltage selection equipment includes a capacitor divider mounted on the roof alongside the circuit-breaker and a potential transformer feeding a group of selector relays in the low tension compartment in the guard's van. A cable from the pantograph is connected to the HT terminal of the capacitor which reduces the line voltage, either 25 kV or 6.25 kV, to appropriate lower voltages which operate either the 25 kV or the 6.25 kV selector relays ; these in turn control the operation of the changeover switch.

40. The selector relays will only allow the air-blast circuit-breaker to close when the input voltages are within the following limits :—

High line voltage : 16.7 kV—27.5 kV or above.
Low line voltage : 4.1 kV— 6.9 kV.

The proving circuit ensures that the changeover switch is operated without load to the appropriate position before the circuit-breaker can be closed. The selector relays also act as the under-voltage relays and open the circuit-breaker if the line volts drop to 15 kV and 3.5 kV respectively on the 25 kV and 6.25 kV sections.

Auxiliary circuits

41. The tertiary winding on the main transformer supplies power for the train heating, the battery chargers, the auxiliary rectifiers through which the ignition and excitation gear of the main rectifiers is energised, and other auxiliary machines, except the auxiliary compressor used for charging the air reservoir for working the pantograph and the air-blast circuit-breaker. This compressor together with the lighting and control circuits is fed from an 110 volts battery.

The main air compressor for the braking system is driven by a D.C. series motor supplied through a single phase bridge connected selenium rectifier from the tertiary winding. The transformer and main rectifier pumps and fans are driven by single phase A.C. capacitor motors taking current from the tertiary winding.

The battery charger

42. Power for charging the 110 volts battery is taken from the tertiary winding through a single phase transductor regulated selenium rectifier from which the D.C. voltage is controlled to close limits.

Protection

43. The air-blast circuit-breaker cannot be closed unless its operating air pressure and the transformer oil level are correct, the voltage changeover switch and measuring relays are in corresponding positions, and the motor circuits are open.

The major protection of the unit is invested in this air-blast circuit-breaker and it is tripped under the conditions enumerated below :

(*a*) When the line voltage drops below the values given in paragraph 40.
(*b*) When the air pressure in the breaker pneumatic circuit drops below a predetermined minimum.

(*c*) When the transformer conservator oil level falls below the required minimum thus causing the oil level switch to open its contacts.

(*d*) When fault currents in the primary winding operate the overload relay OL3. (See diagram.)

44. The traction motor circuits cannot be energised unless the equipment is functioning correctly. To ensure this, the motor contactors (L1 to L4) cannot be closed unless the transformer oil temperature is correct, and the rectifiers are at their correct temperature level and coolant circulation is established. The motor circuits are opened immediately these conditions are no longer maintained.

The motor circuits contain overload relays (OLs 1 and 2) which operate on overload or under limited short circuit conditions ; higher fault levels in both motor and secondary circuits are cleared by the primary overload relay (OL3).

The motor circuits are protected by a combined " no-volt no-current " relay which is energised and retained up to the half voltage tapping by the closing of the circuit-breaker. Beyond half voltage the relay is retained by the motor current only.

Wheel slip protection is provided by means of a relay (W.S.R.) in the equalising connection between the pairs of motors. The operation of the relay prevents further progression of the tapping switch.

45. The protection of the auxiliary circuits is by H.R.C. (High Rupturing Capacity) fuses, except for thermal relays in the rectifier ignition circuit which open to prevent damage to the ignition solenoid should a rectifier fail to ignite. One of these relays is re-set automatically and the other manually.

III. Review of the Running of the G.E.C. Units and of the Troubles Experienced With Them

Trial running of the prototype coach

46. The first 4-car unit with the G.E.C. prototype equipment installed in motor coach No. 501 began trial running on the Colchester-Clacton-Walton lines on 28th October, 1959. These lines which extend for about 24½ route miles were electrified on the 25 kV overhead system and the public electric services began on 13th April, 1959, with trains equipped by the English Electric Company. The distances between stations vary from 1 to 4½ miles and the operating conditions are not onerous.

A half mile section between Alresford and Great Bentley can be energised at 6.25 kV and it has been used to check the operation of the voltage changeover equipment, both of the English Electric and the G.E.C. units. However, the neutral sections at each end have normally been through connected and all the trains have been run at 25 kV except when the changeover equipment was being checked.

47. Motor coach No. 501 ran for 14,600 miles up to 21st March, 1960, when it was returned to Ilford car shed for exchanging the prototype motors for the production types. Some changes were made in control gear but the service records show few failures during these five months.

The coach was returned to passenger service on 5th May, 1960, and ran for a further 10,900 miles until 14th July, when it was withdrawn for the replacement of all the prototype equipment by production types. There was one rectifier cylinder and one tap changer failure during this period.

Altogether this unit ran for 25,500 miles without developing any faults which were thought to be serious.

Commissioning and trial running of the service units on the Colchester-Clacton line 13th April to 28th December, 1960

48. As further G.E.C. units were completed in the Railway Workshops at York and Doncaster they were taken to the Colchester-Clacton line for commissioning, trial running and the training of motormen. All the 70 units of the fleet were tested for varying periods between 13th April and 28th December, 1960. During this period the failures of 14 rectifier cylinders and two battery chargers were reported. The total mileage run during commissioning and testing on this line was 35,800 miles.

Trial running on the N.E. London suburban lines 23rd May to 13th November, 1960

49. Trial running and the training of motormen on these lines began on 23rd May, 1960, when the overhead equipment between Rye House and Hertford East was energised at 25 kV. As further sections of the overhead equipment were completed, trial running was extended towards London. The first 6.25 kV section between Cheshunt and Hackney Downs was brought into use on 30th September, 1960, and by 4th November all the N.E. London lines were ready for the opening of the complete electrified service.

By this date 54 units, excluding the prototype coach No. 501, had been commissioned and run for a total of 50,400 miles—but almost entirely on the 25 kV sections of the line—the other 16 units were commissioned and tested on the Colchester-Clacton lines and sent from there direct into service after the public opening of the N.E. London electrification.

As the regular steam passenger services had to be maintained, trial running was confined to restricted periods and only 22 units were continuously in operation. The others ran for about 200 miles and then were stabled in sidings to await the introduction of the electric services.

50. During this period main rectifier cylinders failed on 21 occasions (see paragraph 69) and there were five failures of battery chargers. No serious trouble was experienced with the control gear, but the tripping of overload relays was a fairly constant feature. Investigation of the blowing of tertiary fuses which was becoming a regular occurrence led to the examination of the transformers as described in paragraph 60 and to the modification of all of them before public services began on the N.E. London lines. There were, however, no transformer failures in service.

There were no traction motor failures during this period, though one was withdrawn from service on account of accidental damage.

As explained in more detail in Section IV the troubles up to this date were still considered to be of a transitory character. It was believed that cures had been found for all of the known defects, and it was decided to adhere to the planned dates for the introduction of the public services.

Limited public service on the N.E. London lines 14th to 20th November, 1960

51. On 14th November after the successful completion of the changeover of the Liverpool Street-Shenfield-Southend electrification from 1,500 volts D.C. to 6.25 kV A.C.—a necessary pre-requisite to the joint user of Liverpool Street terminus and the Ilford car sheds by the new stock and the converted Southend units—a public service on steam timings was introduced and it continued until 20th November.

During this week 40 G.E.C. units were in operation ; some were 4-car sets on the Hertford-Bishop's Stortford lines and the others were 3-car sets on the

Enfield and Chingford services. They were augmented where necessary by English Electric units destined to be used eventually for the London, Tilbury and Southend electrification. The total mileage run by the G.E.C. units during this period was 36,500 miles.

52. Seven more rectifier cylinders failed but they were attributed to deterioration of vacuum while the train sets were stabled in sidings awaiting the introduction of the service. Two more battery chargers also failed, but on units which had not yet been modified (see paragraph 76). There were no motor and transformer failures. Accordingly it was decided to proceed with the full public service as planned.

Full public service on the N.E. London lines 21st November to 11th December, 1960

53. On 21st November the full public services were introduced and 44 G.E.C. units were brought into operation. The intensity of the service can be judged from the table accompanying paragraph 19.

On the first day there were 19 electrical defects as well as some mechanical failures principally associated with the brake equipment. The services were seriously disrupted on this and the following days and much inconvenience was caused to passengers.

Electrical defects of various types occurred from day to day including failures of rectifiers but the most serious disruption of services was caused by the breakdown of traction motors and battery chargers. Altogether 19 motors in 18 units failed between the opening day and 12th December when the service was reduced as explained in paragraph 20 on account of the large number of G.E.C. units that were out of action. Failure of rectifiers and battery chargers numbered 9 and 24 respectively.

The unit mileage run by G.E.C. stock whilst full public services were maintained was 177,000 miles.

Reduced service running 12th December, 1960 to 7th January, 1961

54. On 14th December the first series of modifications, known as the "A" Modifications, were agreed upon and the work was put in hand forthwith (see paragraph 65). It took some time to complete and it was only partially successful. Eight more traction motors failed in this period as well as 15 rectifier cylinders and one battery charger. There was also one failure associated with transformers as described in paragraph 61.

During this period the services on the N.E. London lines were maintained largely by the English Electric units destined for the L.T.S. electrification, and the G.E.C. units were confined to the Chingford branch where delays from failures would not have such widespread repercussions as those occurring on the main lines. Twenty-four 3-car sets were retained for this service and ten units were sent to the Colchester-Clacton line to replace English Electric trains transferred to N.E. London.

The unit mileage run by G.E.C. units during this period was 128,000 miles.

Reduced service running 8th January to 3rd May, 1961

55. A meeting was held on 8th January at the Contractors' works between the Commission and the Contractors, at which Mr. Wheatcroft, Mr. Wilcox and I were present. Another series of modifications known as the "B" Modifications were agreed and plans were made for the equipping and running of a mobile laboratory in a test train as described in Section V. Work on the

"B" Modifications began on 1st February and by 16th March they had been made on 58 units.

56. During the period from 8th January to 16th March failures continued to give serious trouble. They included 21 traction motors on units with the "A" Modifications and one on a "B" modified unit, though in this case and in others which occurred later the failures may well have resulted from damage caused before the second modifications were made. A further 46 rectifier cylinders failed as well as four battery chargers. There were still a large number of control gear defects, one-third of which were due to overload relays, though no other new pattern emerged until towards the end of the period when four tap changers gave indications of breakdown by over-voltage.

The mileage run by G.E.C. units on the N.E. London and the Colchester-Clacton lines during this period was 290,000 miles.

57. Between 17th March and 3rd May the G.E.C. units ran for a further 387,000 miles and improvements were noted in some directions. All the units in service had received the "B" Modifications and although seven traction motors failed they also may have suffered from earlier damage. A unit failed in service on 28th April and on examination was found to have a defective transformer.

Six battery chargers failed and the rectifier troubles continued to be serious, 36 more cylinders having to be changed. As a result of meticulous laboratory examinations and analysis the Contractors decided during this period to make major modifications to the rectifiers as described in paragraphs 71 and 72. These formed part of the "C" Modifications which were agreed upon as a result of the investigations with the test train, to which reference has been made.

58. The table on page 18 gives the summary of the failures and the failure rate per thousand unit miles of the G.E.C. units during trial and service running.

IV. Notes on the Technical Investigations and the Action Taken to Rectify the Defects in the G.E.C. Units

59. The investigations into the main failures of the electrical equipment on the G.E.C. units can best be considered under the following heads :—

(a) Transformers
(b) Traction Motors
(c) Rectifiers
(d) Battery Chargers
(e) "C" Modifications

Transformers

60. The first serious troubles with the G.E.C. units arose when trial running was in progress on the N.E. London lines (see paragraph 50). The most serious were those associated with the transformers and on 2nd September, 1960, a meeting was held between the Commission and the Contractors to resolve the matter. One transformer had been returned to the Contractors' works and two others were examined at the railway shops.

All three had sustained the same type of damage. The internal connections for the tertiary windings had been seriously distorted and had touched the side of the transformer tank, thus causing the faults to earth, which had blown the tertiary fuses. The screw assemblies supporting the end clamps for the secondary and tertiary windings had buckled. None of the windings had broken down and there was no noticeable distortion or displacement of the conductors. These troubles were undoubtedly due to short-circuits which had occurred during trial running.

Failures of G.E.C. units during trial and service running

	Trial running			Service running N.E. London and Colchester-Clacton lines				
	Colchester-Clacton lines		N.E. London lines	Steam timing	Full electric service	Reduced electric service		
	Prototype	Commissioning						
1. Period	28th Oct., 1959 to 14th July, 1960	13th April to 28th Dec., 1960	23rd May to 13th Nov., 1960	14th-20th Nov., 1960	21st Nov. to 11th Dec., 1960	12th Dec., 1960 to 7th Jan., 1961	8th Jan. to 16th Mar., 1961	17th Mar. to 3rd May, 1961
2. Unit miles run	25,500	35,800	50,400	36,500	177,000	128,000	290,000	387,000
3. Failures :								
(a) Motors	0	0	0	0	19	8	22	7
(b) Rectifiers	1	14	21	7	9	15	46	36
(c) Battery chargers	1	2	5	2	24	1	4	6
4. Failure rate per 100,000 unit miles :								
(a) Motors	0	0	0	0	11	6.2	7.6	1.8
(b) Rectifiers	3.9	39	42.	19	5.1	12	16	9.3
(c) Battery chargers	3.9	5.6	10	5.5	13	0.8	1.4	1.5

It was decided to strengthen the clamping arrangements and to stiffen the supports of the winding connections. All the transformers were returned to the Contractors' works for modifications which were completed before the N.E. London public services on steam timings were opened on 14th November.

61. Two other failures have been associated with the G.E.C. transformers. In both cases serious external short-circuits were experienced and the two transformers were returned to the Contractors' works for stripping and examination.

On 22nd December, 1960, a serious flashover occurred in the tapping switch case of the transformer in Unit No. 444 which was extensively damaged, possibly due to a flashover on a surge diverter leading to a sustained short-circuit. The fault involved a number of the secondary tapping sections.

When this transformer was inspected, it was found that there had been some displacement of the end turns of the secondary coil assembly, and noticeable indentation of certain end packing blocks. The tapping connections within the transformer assembly had become overheated and had short-circuited at a point where they were strapped together and stiffened by insulating board. The beginnings of conductor displacement were apparent, but the strengthened clamp supports were undisturbed.

62. On 21st January, 1961, a similar flashover occurred in the tap changer compartment of the transformer in Unit No. 433, but it had been cleared much more quickly. This transformer was also known to have suffered a number of short duration short-circuits due to rectifier troubles.

In one coil some of the conductors appeared to be very slightly twisted but there was no other evidence of winding distortion or of clamping displacement.

63. Both transformers were inspected by Mr. Lane and his staff. Mr. Lane concluded that the sustained fault on the first of these transformers was an exceptional occurrence, the damage resulting from which did not justify doubts about the satisfactory performance of other transformers in service. This conclusion was confirmed by the condition of the second transformer.

On 28th April Unit No. 519 broke down in service. The cause was diagnosed on 11th May as a transformer failure and reported to me. This transformer and four others, including the one in the test train, were returned to the Contractors' works for detailed examination to see whether they showed any signs of damage. At the same time a transformer was subjected to short-circuit tests in accordance with Mr. Lane's requirements. The results of these investigations are given in paragraph 135.

Traction motors

64. As already mentioned in paragraph 50, no motors failed during trial running, but one was withdrawn from service on account of accidental damage; there was no indication of the troubles to come. None failed during the week of limited public service from 14th to 20th November, but when the full intensive service on the faster electric timings began on the next day, the first motor failure occurred, and this was followed by many others. As a result it was decided to withdraw most of the G.E.C. trains. A meeting between the Commission and the Contractors was held on 9th December to consider this serious situation and to review the investigations which had been put in hand immediately it was realised that the motors could not withstand the arduous conditions to which they had been subjected.

65. By this time a number of the damaged motors had been examined and a series of tests had been made by the Contractors. The failures were confined

principally to traction motors in the 3-car units operating on the Chingford and Enfield lines where, as explained in paragraph 18, conditions are severe. In almost every case short-circuits to earth had occurred at two or three places in the motor field circuit and one of the faults had always been on an interpole. In all cases the coils and the associated details had been severely damaged.

A series of modifications known as the "A" Modifications were agreed and they included the fitting of new surge absorbers across the motor chokes and the checking and adjusting of overload relays. At the same time the Commission's engineers asked that consideration should be given to the earthing of the traction motor at the mid-point connection, but this and other alterations were not finalised until later.

66. On 6th January, 1961, as already mentioned, Mr. E. L. E. Wheatcroft was appointed by the Commission to make an independent investigation of the G.E.C. failures. On 8th January he and Mr. T. W. Wilcox attended an important meeting between the Commission and the Contractors, at which I also was present. Mr. W. D. Morton, Assistant General Manager of the G.E.C. Works at Witton, presented a comprehensive report setting out the troubles which they had experienced, the tests they had made and the modifications they recommeuded. He explained that up till then his engineers had attributed the traction motor troubles to surges developed in the motor chokes where the original diverters had proved to be inadequate. Since the "A" Modifications had been made, five motors out of 40 units so modified had failed, and the conclusion had just been reached as a result of these failures and further laboratory tests that the source of most, if not all, of the trouble lay in transient over-voltages developed by the air-blast circuit-breaker when " chopping " on 6.25 kV. They believed that these over-voltages created surges in both the secondary and tertiary circuits of sufficient magnitude to cause not only the failures of motors but also of the rectifiers and battery chargers.

67. Some tests had been carried out with measuring instruments in a train in service but at this meeting it was decided that a much more detailed examination was needed of the effects of transient over-voltages on the various current circuits during normal and abnormal operating conditions. The Contractors announced that they would equip a train as a mobile laboratory and provide a full team of observers to carry out all tests which they (the Contractors), the Consulting Engineers, and the Commission might consider desirable. A description of this train and the results achieved with it are given in Section V.

68. It was also decided to make another series of modifications, known as the " B " Modifications, in anticipation of the theories now put forward by the Coutractors being correct. These modifications included the provision of an earth and an earth fault relay at the mid-point of the motor circuit and the insertion of a 10 K ohm resistor to earth at the mid-point of the transformer secondary circuit. Three surge divertors were also to be fitted at three points in the former secondary circuit.

The improvement in motor behaviour as a result of these modifications has already been noted in paragraph 57.

Rectifiers

69. Rectifier troubles began during trial running and they have persisted throughout. They featured in all the discussions between the Commission and the Contractors, but until early in December the Contractors did not consider that anything was seriously wrong. A number of rectifier cylinders which had failed during trial running were returned to the Contractors' works for examina-

tion. The majority of failed rectifiers had lost vacuum but on examination a number of cylinders which had withstood severe flash arcing were found to be in perfect condition internally.

70. By the end of the year, however, the Contractors began to realise that something was radically wrong with the rectifier design and that the continued failures could no longer be associated with initial "teething" troubles. The position was reviewed during the meeting on 8th January and it was thought that some of the rectifier troubles were associated with transient over-voltages. It was decided to continue laboratory investigations and also to carry out further tests to ascertain the cause of the troubles. These were undertaken in conjunction with the running of the test train, but it was difficult to obtain any positive results.

71. Eventually as a result of intensive laboratory research the failure of the main anodes and the loss of vacuum was traced to a complex metallurgical condition in parts of the anodes which were repeatedly subjected to high thermal stresses which resulted in fatigue failure. A modified form of anode to eliminate failures of this nature is now being incorporated in all the rectifier cylinders. This should stop loss of vacuum.

72. It was found in the course of the test train trials that flash-arcs, i.e. backfires of a duration of less than one ½-cycle, frequently occurred when trains were left standing for long periods with the rectifiers energised but not passing load current. The power circuits are now being modified so that they are physically interrupted when the controller is in the "off" position, thus ensuring that the rectifiers are always disconnected when the equipment is idle.

The Contractors consider that the flash-arcs which can momentarily allow current many times full load to pass through the rectifier are caused by mercury condensation which can be cured by keeping the anode hot. The rectifier equipment is now being modified by the provision of "dual" cooling, whereby the 8 anodes are in one cooling circuit and the 8 cathodes in the other. By this means a suitable temperature difference can be maintained in the rectifier under all conditions.

73. The three modifications noted above form part of the "C" Modifications to which further reference is made in paragraph 79. They should go far to eliminate the defects from which these rectifiers have suffered.

74. It is a feature of the G.E.C. Com-Pak rectifier that each time voltage is excessively reduced or lost on the excitation circuit, either from arcing or interruption of current at the pantograph, the rectifiers have to be re-ignited, and due to the nature of the excitation gear there is a limit to the number of re-strikes which can be made in rapid succession.

Beyond four or five rapid break/make operations of the A.B.B. the rectifier excitation may "lock out" for a short period and then come back into action after an undetermined time.

In the case of the rectifiers on the test unit the recovery time varied between 1 and 8 seconds with individual cylinders. In such circumstances conditions can arise during which for a short time some of the rectifiers are excited and others are unexcited ; this may set up what is known as half-wave conditions, i.e. the normal D.C. motor current is changed into a pulsating half-wave current. If during this condition a further tripping of the A.B.B. occurs with the motor contactors closed, the stored energy in the motor smoothing chokes, which may be considerable, will cause the generation of surge voltages.

75. During the course of test runs it was discovered that loss of contact between the pantograph and the overhead conductor occurred at one or two places on

the system ranging from a single interruption up to as many as 14 successive disturbances in a few seconds at speeds of 45 m.p.h. and over. The effect of such interruptions formed a special feature of the test train investigations which is discussed in the next Section. No immediate cure has been found for the "lock out" of rectifier excitation, but further laboratory experiments are in hand.

Battery chargers

76. There have been a number of failures of battery chargers. Some of them were initiated by switching surges on the tertiary windings which caused over-voltages to be generated within the chargers themselves. It was found that this trouble could be alleviated by fitting resistance capacitor suppressors across the transductors, but as this was not a complete cure all the transductors were later re-wound, with very much increased insulation between turns and the suppressors were no longer neccessary. These changes effected considerable improvements.

This equipment is similar to that installed in the English Electric units now operating in the Eastern Region and the failure rate has been comparable to that of the battery chargers in the G.E.C. units.

Failures have continued, though at a reduced rate, and it is now considered that the selenium rectifiers themselves have not always been able to withstand the high transient over-voltages in the tertiary circuits to which Mr. Wheatcroft refers in his interim statement—see Section VI. The "B" and "C" Modifications now being made will reduce these over-voltages, but not eliminate them, and consequently the selenium rectifiers will have to be replaced by others having a higher over-voltage margin.

"C" Modifications

77. Following the decision taken on 8th January to equip a test train and carry out a comprehensive examination of the problem, further meetings have been held between the Commission, the Contractors and the Consulting Engineers at some of which I have been present. The chief object has been to watch the progress of the test train and to consider what further modifications would be desirable as a result of the additional information obtained.

78. Although the majority of the over-voltage breakdowns occurred on traction motors, the troubles included breakdowns to earth on other items of equipment, such as rectifier ignition equipment, rectifier tanks and transformer surge divertors, as well as failures to battery chargers. An investigation of these troubles was therefore included in the remit to the test train team.

79. As a result of the information obtained during the early days of the test it was decided on 10th March to make further alterations known as the "C" Modifications. Those affecting the rectifiers have already been described. Other important changes were :—

(*a*) The addition of a protective capacitor/resistance unit across the transformer secondary winding.

(*b*) An improved spark-gap device for the motor smoothing choke.

(*c*) The replacement of the OL3 overload relay by one of improved type.

V. The G.E.C. Test Train

80. At the meeting on 8th January the G.E.C. announced that they would equip a train as a mobile laboratory and provide a team of observers to discover the conditions giving rise to the high transient over-voltages which they believed had damaged the traction motors. At a further meeting two days later the

Contractors and representatives of Messrs. Merz and McLellan discussed the equipping of the train and the type of information to be recorded.

81. Unit 408 was selected for the test and the saloon of the motor coach was partly stripped of seats to accommodate the large amount of test equipment. The coach was fitted out at the Contractors' works at Witton, near Birmingham, and on 30th January it was sent to the Eastern Region's electric car shed at Ilford. Some time was needed for checking and calibrating the instruments and in making adjustments so that they would withstand the vibration and movement associated with railway traction. Unit 446 was coupled to the test unit thus making up a 6-car train.

82. The train began operations on 16th February on the Liverpool Street-Chingford-Enfield lines, all energised at 6.25 kV. Up to 31st April some 3,000 running tests, including many hundred static tests, were made as summarised below.

The test equipment

83. Since the principal object of the service testing was to discover the conditions under which the over-voltages were produced, the measuring equipment had to be capable of recording reliably various phenomena of extremely short duration which might occur at any moment during the course of the tests.

84. Six Cathode Ray Oscillographs (C.R.Os) were installed ; two of these were specially designed for recording very short duration surges and the remainder were standard types adapted for the purpose. All the instruments were arranged so that the electron beam would scan the screen once at high speed and trace out the wave-shape of the transient whenever the applied voltage exceeded a pre-set level. A camera was mounted on the front of each instrument with an open shutter, so as to be ready at all times, to record random incidents during the progress of programmed tests.

Capacitor dividers were connected at selected positions in the main power circuit, to feed proportionally scaled-down signal voltages to the instruments. The measuring points covered the pantograph, transformer primary, transformer secondary, transformer tertiary, and the traction motor circuits, as indicated on the diagram on page 8. In addition, signals proportional to primary current and D.C. motor current were available for measurement. In order to identify the position in sequence of the tap changer, a pulse counter was designed, energised by the notching up of the tap changer. The signals operated a row of lamps in sequence and could also be recorded on a chart.

A 12-channel Ultra-Violet Oscillograph was employed as a continuously running event recorder and twelve of the available quantities were fed to its galvanometers. A chart was thus produced, having a variable rate of feed giving an immediate indication of all variations of the monitored quantities.

85. Meter indication of the primary current, the tertiary current and the train speed was also provided in the test coach. A large number of the tests involved the opening of the air-blast circuit-breaker (A.B.B.) on either of the units forming the test train, and switches were fitted in the test saloon for this purpose, together with lamps showing whether a breaker was closed or open. A further three lamps indicated the tripping of any of the three overload relays on the test unit.

A " point-on-cycle " pulsing device was constructed to enable the opening of the A.B.B. on the test unit to be initiated at any predetermined point on the cycle. This unit could also be arranged to trigger off up to four of the C.R.Os in synchronism with the opening of the A.B.B.

86. Further hand-operated switches were also fitted for :—

(a) switching off the excitation of either four or all eight rectifiers ;

(b) rapid multiple opening and closing of the A.B.B. ;

(c) synchronising the de-excitation of rectifiers with the tripping of the A.B.B. ;

(d) short-circuiting certain interlocks in the control circuits.

87. In order to monitor the behaviour of the rectifiers, equipment was installed in the test saloon to register all re-ignition or flash-arcs of each individual cylinder.

88. Equipment was also installed in the guard's van of the test unit which could be connected in circuit experimentally for suppressing surge voltages. This consisted of a variable capacitor and series resistance connected across the transformer secondary and a further capacitor/resistance unit across the tapping choke.

89. Continuous voice inter-communication between test saloon, driving cabs and Unit 446, vital to the success of the testing, was installed.

90. The test apparatus required a 240 volts A.C. supply of up to 3 kW, to be independent of fluctuations in the overhead line supply. To this end, a large 110 V battery was used to drive two motor alternator sets which were installed on Unit 446, cables being run up to the test saloon on Unit 408.

91. A G.E.C. team of twelve Engineers was required to carry out the tests, in addition to the railway train and liaison staff. A representative of the Consulting Engineers was also present throughout.

Summary of tests

92. As already mentioned some 3,000 programmed tests have been made and in addition numerous records have been taken of random incidents leading to over-voltages. Several hundred static tests were made with the train in a siding, either at Chingford or Wood Street.

93. The programmed tests comprised the opening of the A.B.B. under all the various operating conditions of the train. The variables involved included :—

(a) The position of the master controller and of the tap changer in its notching sequence.

(b) The position of the train in relation to the feeder point.

(c) The train speeds.

(d) The primary or line current.

(e) The loading on the transformer tertiary winding.

(f) The excitation conditions on the rectifiers.

(g) The point-on-cycle of the A.B.B. opening.

The majority of the tests were carried out with the minimum service loading on the tertiary winding as it had been found that the coach heating load reduced the level of surges considerably.

94. Testing up to 12th March was carried out with the unit in the "A" modified condition (i.e. mid-point of motors not earthed) with the addition of a protective capacitor unit to prevent premature failure of equipment : this became a major Group " C " Modification (see paragraph 79). All tests after that date have been in the " B " modified condition (i.e. mid-point of motors solidly earthed), some with and others without the protective capacitor.

95. Circuit conditions used for opening of the A.B.B. of the test unit included :—

(a) Master Controller in notch 1 (see paragraph 36) at various speeds.

(b) Master Controller in notches 2, 3 and 4 at various speeds.

(c) Master Controller in the " off " position, i.e. with the train " coasting ".

(*d*) Tap-changer in course of notching up, or running back to the "off" position.

The conditions were applied with normal rectifier operation and also with the rectifiers operating in a deliberately induced half-wave condition.

The latter tests were designed to simulate the conditions following multiple interruption of the current at the pantograph, which, due to certain features of the rectifier excitation, may lead to temporary half-wave conditions. A further opening of the A.B.B. can then lead to the generation of severe surges.

Tests were also carried out with :—

(*e*) A rapid break/make of the A.B.B. with the Controller in position 1. (Rectifiers operating normally.)

This simulated the condition of a single momentary loss of contact between the pantograph and overhead line.

(*f*) A rapid make/break of the A.B.B. with the Controller in the "off" position.

This simulated the closing of the A.B.B. when leaving a neutral section, followed by its immediate tripping due to the operation of the OL3 relay on transformer inrush current.

(*g*) The A.B.B. of Unit 446 opened under various normal running conditions, to examine its effects upon the test unit.

Some tests were carried out without surge suppression, and others with various degrees of suppression across the transformer secondary winding.

Results

96. A complete analysis of the test train and laboratory results is being prepared by the Contractors' Engineers in conjunction with the Consulting Engineers. It will not be available for some time but it can be stated that the tests confirmed that severe over-voltages could be produced by the action of the A.B.B. when running on 6.25 kV with no secondary suppressor fitted to the transformer.

The worst conditions affecting all the transformer windings arose with :—

(*a*) The A.B.B. tripping with the rectifiers in the half-wave condition. (Up to 7 times the normal peak.)

(*b*) The rapid make/break of the A.B.B. when re-energising after leaving a neutral section. (Up to 6 times the normal peak.)

(*c*) The A.B.B. tripping with the Controller on first notch, and rectifier excitation normal. (Up to 4.5 times the normal peak.)

(*d*) The A.B.B. tripping under normal coasting conditions, e.g. when entering a neutral section with the Controller in the "off" position. (Up to 3.5 times the normal peak.)

With the earth connection at the mid-point of the transformer, condition (*a*) produced over-voltages in the motor circuit of more than 10 kV. When the earth connection was changed to the mid-point of the motor circuit these over-voltages became negligible but voltage surges of over 12 kV to earth were measured on the secondary winding under conditions (*a*) and (*b*) with surges of nearly 2.5 kV in the tertiary winding.

97. The addition of a suppressor on the transformer secondary winding proved effective in limiting the surges to a much lower level. With a 5 microfarads capacitor in series with a 20 ohms resistor across the secondary winding and with the earth at the mid-point of the motor circuit the highest voltages to earth recorded under the worst conditions ((*a*) above) were :—

26 kV	on the primary compared with a normal peak of	8.9 kV
5.6 kV	,, ,, secondary ,, ,, ,, ,, ,, ,,	2.3 kV
980 volts	,, ,, tertiary ,, ,, ,, ,, ,, ,,	380 volts

It has been calculated that the conditions producing these voltages will in turn produce maxima of 5 kV across the D.C. smoothing chokes and 10 kV across the secondary tap changer; it is considered, however, that these voltages will not cause any damage to the equipment.

Various additional means for the suppression of the tertiary voltage to lower values were tried but so far without success.

98. During the course of the tests with the A.B.B. tripping with the main rectifiers operating on half-wave, the battery charger unit failed due to voltage breakdown of one of its auxiliary rectifiers. This unit was replaced and test running was resumed, but after only 40 minutes a traction motor failed also, the interpole coils being earthed due to the puncturing of the insulation. The small time interval between the two failures makes it almost certain that they were both caused by the same surge. This occurred when the earth connections were still at the mid-point of the transformer and without the addition of a protective capacitor. This failure demonstrated dramatically the effect of over-voltage on the motor circuit as originally planned and confirmed the theoretical conclusions.

Other possible causes of over-voltages

99. A number of other possible causes of over-voltages were examined, with the following results :—

(1) The interruption of the current at the pantograph. No direct evidence of serious over-voltages was found, but the position was somewhat confused by the almost simultaneous opening of the A.B.B. Some running has been carried out with the A.B.B. prevented from opening under pantograph interruption conditions, but no significant surges have yet been recorded, although further test work is being done on this condition.

(2) The interruption of the current by motor contactors. During the many hundreds of operations performed by these contactors, no significant surge voltages were recorded.

(3) Current chopping and flash-arcing within the rectifiers. Nothing in the test results up to date indicated this to be a major source of trouble to the motors.

(4) Externally impressed surges from the overhead line supply. No cases of this were revealed. The supply voltage was subject to some fluctuation, and considerable distortion of its wave-form due to the action of other trains was observed, but there were no violent disturbances.

Behaviour of rectifiers

100. Whilst a considerable number of flash-arcs occurred during night periods when the train was left with its pantograph up, very few occurred whilst testing was in progress. Of the latter group none gave rise to surge voltages or tripping of the OL3 relay. Some flash-arcs were deliberately induced by mechanical impact by allowing abnormally high coolant temperature, and by fitting suspect rectifiers, but no significant surges were recorded.

Intensive testing of the rectifiers on the test unit is continuing.

Random incidents producing over-voltages

101. A detailed analysis of all results is not yet finally complete, but it can be stated at this stage that a number of incidents leading to substantial over-

voltages have been recorded. (Maximum to date: 47 kV on the Primary; 8.4 kV on the Secondary; 1.12 kV on the Tertiary.)

This is an important aspect of the testing, since it reflects the operation of the equipment in normal running. There have, however, been no cases of random incidents producing over-voltages greater in value than those observed during the programmed tests.

VI. Messrs. Merz and McLellan's Interim Statement

102. Mr. E. L. E. Wheatcroft, a partner of Messrs. Merz and McLellan, has sent to the Chief Electrical Engineer of the British Transport Commission an interim statement on the investigations carried out by his firm, and it is given in full in the accompanying paragraphs, to which I have added serial numbers to keep in sequence with my report:—

"Dear Sir,

Interim Statement on Failures on Multiple-Unit Trains on the Eastern Region

103. In accordance with your instructions we have made an intensive investigation into the failures which have occurred with traction motors on multiple-unit trains equipped by the G.E.C. for the Eastern Region suburban electrification. We will be submitting to you a full report giving details of our present findings together with particulars of the modifications which are recommended to prevent further failures of the existing stock. We believe, however, it is appropriate at this stage to make an interim statement summarising the results of our investigation so far, since we consider that the causes of the failures of the traction motors have been established and remedial work has been put in hand. At the same time we find it necessary to refer briefly to the causes of failure of the main mercury arc rectifiers which have still to be finally resolved.

104. The investigations made so far have included theoretical studies, discussions with designers and operating staff, examination of damaged equipment, laboratory tests in the manufacturer's works and more than two months first hand experience with a specially equipped 'mobile laboratory', in which the electric traction equipment has been subjected to about three thousand tests under normal and abnormal operating conditions.

Many of the important phenomena encountered have been found to be of a transient nature occurring in a random manner, and these have proved difficult to measure and analyse. For example, the effects on the various electric circuits of simultaneous or sequential arcing conditions in the rectifiers, in the air-blast circuit-breaker and at the pantograph current collector have been particularly difficult to study, and many special problems of applying normal laboratory oscillographic techniques on a moving train have had to be overcome.

105. The failures which had caused most dislocation of the electric service were those which involved the traction motors, the mercury arc rectifiers and to a lesser degree the battery chargers.

106. Our investigations have revealed no reasons to suspect the design or workmanship of the traction motors, and it has now been definitely established that the traction motors were damaged by fault currents resulting from breakdown of the insulation of the windings by switching over-voltages.

107. It was found that the most severe switching over-voltages to which the motors were subjected were those encountered when the A.C. air-blast circuit-breaker opened during a period in which the normal D.C. motor current had

been changed into a pulsating 'half-wave' current by a temporary loss of excitation on some of the rectifiers. These conditions occurred when intermittent loss of contact between the pantograph and the overhead contact wire caused, first, the excitation of some of the rectifier igniters to lock out much earlier than others and so produce half-wave current rectification, and, secondly, the air-blast breaker to trip due either to the inrush magnetising current resulting from repeatedly re-energising the transformer or other effects of intermittent loss of contact.

Under these conditions the discharge of the energy which was trapped by the operation of the circuit-breaker in both the D.C. smoothing chokes and the A.C. transformer caused high transient over-voltages to be impressed on the motor windings.

108. It was also found that other only slightly less severe over-voltages occur when the air-blast circuit-breaker is tripped by a heavy inrush current immediately after energising the transformer. These over-voltages, however, are not applied to the motors.

109. The main objects of the experimental verification of these and other phenomena were first to determine the magnitude of the over-voltages which could occur on the motors with the original earthing arrangement (in which the secondary circuit was earthed at the mid-point of the transformer secondary winding) under which the motor failures had occurred. Secondly, it was required to determine the values of the over-voltages obtained when the mid-point of the motors instead of the mid-point of the transformers was earthed; and thirdly to establish the magnitude of the over-voltages on the tertiary windings under both of these conditions.

110. A full appreciation of the over-voltages which may occur in the various circuits cannot be obtained directly from study of the maximum values recorded during the tests, and it has been necessary to deduce the worst conditions which can occur in service taking account of:—

(a) the statistical increase necessitated by the random nature of the phenomena and the limited number of tests made of each condition;

(b) the relationship of the voltages to earth at the measuring points and the corresponding values between various points of the circuit;

(c) the relationship between the circuit parameters under which the tests were actually made and other combinations of these parameters which occur in service, e.g. the effect of locking out various combinations of rectifiers in the bridge circuits.

111. Taking these factors into account the test results indicate that in the original arrangement in which the earth point was made at the transformer, the motors were subjected to peak over-voltages to earth of more than 10 kV, which greatly exceed the values which the insulation of the motors can be expected to withstand.

112. With the earth point at the motors the over-voltages across the motor insulation were negligible, but the over-voltages to earth on the D.C. smoothing chokes and tap changer could be about 10 kV and 20 kV respectively. It is expected that the insulation of the D.C. smoothing chokes would be able to withstand 10 kV, but the insulation of the tap changers is not adequate to withstand 20 kV.

113. The method of earthing the motor circuit did not affect the peak over-voltages on the tertiary windings, which were about 2.5 kV and thus greatly exceeded the safe values for the battery chargers and auxiliary rectifiers.

114. During the course of the half-wave current tests a breakdown occurred on the windings of one of the motors, and one of the battery charger rectifiers also failed because of the high over-voltages to which it had been subjected.

115. No tests were made on 25 kV sections of the line, but under such conditions the magnitude of the over-voltages encountered on the secondary and tertiary windings of the transformer will be only about one quarter of those experienced when running on 6.25 kV sections of the line. This is because the peak values of the primary over-voltages are largely determined by the inherent characteristics of the air-blast circuit-breaker and are approximately the same in both cases, whereas the peak over-voltages impressed on the secondary and tertiary windings are approximately proportional to the transformation ratios.

116. The tests also showed that the surge diverters provided on the secondary winding of the transformer and elsewhere did not adequately suppress the over-voltages.

117. As mentioned earlier the changes to the earthing arrangements materially reduce the over-voltages on the motors. These changes, however, will not reduce the stresses on the D.C. smoothing chokes, and moreover have the effect of increasing the stresses on other parts of the secondary circuit insulation, notably the transformer secondary winding and tap changer. Consequently additional over-voltage protective devices are to be provided between the high voltage terminals of the D.C. smoothing chokes and earth, and also across the secondary winding of the transformer. The latter will consist of a 5-microfarads capacitor in series with a damping resistor, and the former will comprise a spark-gap having a high current-carrying capacity connected in series with a current-limiting resistor.

118. An experimental capacitor/resistor protective device was fitted to the test train, and the switching tests under conditions of half-wave current rectification were repeated. From the results of these tests we conclude that, with the earth point at the motors and the provision of the protective devices mentioned above, the maximum over-voltages to earth on the D.C. smoothing chokes and tap changer do not exceed 5 kV and 10 kV respectively. It is expected that the insulation of the D.C. smoothing chokes and tap changer will withstand these over-voltages successfully.

119. It was also found that the effect of this protective device on the tertiary winding over-voltages was to reduce the peak measured values from 2.5 kV to about 1 kV. The existing auxiliary rectifiers are not capable of withstanding more than about 0.66 kV, and even by applying additional protective devices directly to the tertiary winding it was not possible to limit the over-voltages to below this value. It is accordingly recommended that the existing auxiliary rectifiers be replaced by rectifiers capable of withstanding voltages up to at least 1.2 kV.

120. The fundamental cause of the failures of the main mercury arc rectifiers is not yet conclusively established. The majority of rectifiers which have failed have lost vacuum, and air or cooling water has entered the rectifier cylinders through cracks in the steel anodes. Investigations have revealed high mechanical stresses and metallurgical failure in the anode material, which have led to fractures of the metal.

Modified cooling and re-design of the anodes and other modifications to eliminate these and other less serious troubles is proceeding, and the investigation, testing and proving continues. The G.E.C. are confident that with these modifications the rectifier failures will be eliminated.

There are sound reasons for thinking that the manufacturer's proposals will lead to a satisfactory solution, but this can only be proved under service conditions.

Yours faithfully,
E. L. E. WHEATCROFT
for MERZ AND MCLELLAN."

VII. THE MODIFICATION AND TESTING OF THE GLASGOW SUBURBAN ELECTRIC STOCK

121. Good progress has been made with the modification of the Glasgow suburban multiple-unit trains. All the new transformer windings have been made and by 3rd May 68 transformers had been completed to the new design, to which I referred in my first interim report. The full resources of the Manchester and Rugby Works of the A.E.I. were used, as promised by Mr. H. West, the Managing Director. The modification of the coaches is being carried out at the Dukinfield Railway Works near Manchester, which were made available by the London Midland Region. Work on 48 coaches had been completed by 3rd May.

The modified design of the transformer was type-tested satisfactorily on 22nd February, and the first reconstructed train comprising two 3-car units was subjected to oscillographic and other tests during the nights of 21st, 22nd and 23rd March.

122. Since that date the number of units in Scotland has been increasing at an average rate of 5 per week and on 3rd May 32 units were available for trial running and driver training. It is intended that the first reconstructed train on which tests are being carried out will be run for some 20,000 miles, and all others for about 2,000 miles each before being introduced into the public service.

123. The task of reconstruction has been a formidable one because, in addition to rebuilding the transformers, a number of other modifications and improvements have been introduced as a result of the experience gained during service running before the electric trains were withdrawn on 17th December last.

The modifications detailed in my interim report have been carried out and, in addition, the ventilating arrangement of the main rectifier has been further improved so as to eliminate as far as possible this major cause of backfire. It is also of interest to record that, although there have been no failures of traction motors of any kind, a capacitor resistance network has been fitted across the secondary to suppress the transient over-voltages in the tertiary circuit. In addition to the fault indicators in the guard's van, another indicator has been provided in each motorman's cab, by which the motorman can tell at once if any circuit-breaker is open.

124. The enquiry by Mr. Lane, in association with the engineers of the Commission, the Scottish Region and A.E.I., into the reasons for the excess current conditions which caused the collapse of the original transformer secondary windings has necessitated an extensive series of tests, both in the works and on the track, together with an examination of a large number of operational records. I shall refer in more detail to this subject in my final Report.

These tests are continuing and others are in hand to prove that the modifications which have been introduced will ensure a satisfactory service. Experience with the reconstructed trains has not, however, given rise to any doubts as to the effectiveness of the modifications which have been made.

125. As explained in my introductory remarks this second interim report is principally concerned with the failure of electrical equipment installed by the General Electric Company in multiple-unit trains running in the Eastern Region.

126. Up till the end of April when a transformer failed in service there had been three main causes for the breakdown of the G.E.C. units, namely :—

(a) The failure of a traction motor arising from short circuits to earth in the motor field circuit.

(b) The breakdown of one or more of the mercury arc rectifiers principally on account of loss of vacuum.

(c) The failure of a battery charger resulting in the exhaustion of the 110 volt battery which supplies power for the lighting, heating and control circuits, as well as for the auxiliary air compressor.

127. Virtually all of these failures have occurred on the North East London lines where the dual voltage system is in use, and except for rectifier cylinder failures which have persisted throughout, the operation of trains on the Colchester-Clacton line, which is energised at 25 kV, has generally speaking been trouble free. Furthermore, the serious breakdowns of traction motors did not begin until the full public service on the intensified and accelerated electric timings was introduced on the North East London lines on 21st November.

The causes of the troubles were difficult to trace. Those affecting the motors and some of the battery chargers were primarily the result of transient over-voltages of high magnitude developed by the opening of the air-blast circuit-breaker when trains were operated on the 6.25 kV sections of the North East London lines. These surges affected both the secondary and the tertiary circuits and they resulted in the breakdown of insulation in the motors and in the auxiliary rectifiers of the battery charger. It was also thought that the main rectifier troubles sprang from the same source, but eventually it was discovered that the cause was mechanical and thermal rather than electrical.

128. Mr. E. L. E. Wheatcroft, a partner of Messrs. Merz and McLellan, who was appointed to make an independent investigation into the cause of the failures of the G.E.C. equipment, has prepared an interim statement which is set out in Section VI. I accept his conclusions that the design and the workmanship of the traction motors is satisfactory and that it has now been definitely established that the motors were damaged by fault currents resulting from a breakdown of insulation on account of switching over-voltages.

129. He has set out in his statement the chief causes for these over-voltages and he has made it clear that their effect on the transformer secondary and tertiary windings are some four times greater when operating on the 6.25 kV sections of the line than on the 25 kV sections. This is because the primary over-voltages are largely determined by the inherent characteristics of the air-blast circuit-breaker and they are approximately the same when operating on either line voltage, whereas the step down ratio to the secondary winding is four times greater on 25 kV than it is on 6.25 kV. This is on account of the four sections of the secondary winding being connected in series when the overhead line is charged at 25 kV and in parallel when it is charged at 6.25 kV. The effect of over-voltages on the secondary winding is transmitted proportionately to the tertiary winding which is thus subjected to similar heavy surges when the motor units are operating on the lower line voltage.

130. The over-voltages which caused the breakdown of the traction motor insulation have been practically eliminated by moving the earth connection for the secondary circuit from the mid-point of the transformer winding to the mid-point of the motor bridge circuit, thus reducing substantially the amount of the voltage surges which can appear across the motor field insulation.

131. As a result, however, the over-voltages to earth through the D.C. smoothing chokes and those through the transformer secondary tap changers have been increased. To cope with this, additional protective devices are being provided and they form part of the "C" Modifications detailed in paragraph 79. An improved type of spark-gap having a high current carrying capacity will be connected in series with a current limiting resistance to take care of the D.C. smoothing choke. A capacitor in series with a damping resistance will be fitted across the secondary winding to suppress the voltage surges which might otherwise appear across it and the tap changers. These safeguards will also reduce the over-voltages which can pass through the tertiary circuits from peaks of about 2.5 kV to about 1 kV, but these are still more than $2\frac{1}{2}$ times greater than the normal peak. The existing selenium auxiliary rectifiers used in connection with the battery chargers and also for the ignition and excitation gear of the main rectifiers are, however, not capable of withstanding much more than 660 volts. Consequently, the Contractors are replacing them by rectifiers capable of withstanding a much higher voltage.

132. As Mr. Wheatcroft points out, the fundamental cause of the failures of the main mercury arc rectifiers has not yet been conclusively established, but I accept his view that mechanical failure and unsuitable cooling arrangements have been a major cause of these troubles, though in addition some of the ignition and excitation rectifiers did not withstand the tertiary over-voltages to which they had been subjected. The Contractors are confident that the modifications outlined in paragraphs 71 and 72 will be effective, but this can only be proved under service conditions.

I recommend, however, that consideration be given to re-designing the rectifier excitation gear so as to increase the number of re-strikes which can be made in rapid succession and so eliminate the "lock out" of rectifier excitation which has been the cause of some of the excessive voltage surges to which I make reference in the next paragraph.

133. It has been established by the test train results and confirmed by Mr. Wheatcroft's analysis that the most serious over-voltages are generated when the air-blast circuit-breaker opens when the normal D.C. motor current is changed into a pulsating "half-wave" current by the temporary loss of excitation on some of the rectifiers. This phenomenon arose when the loss of contact between the pantograph and the overhead wire (pantograph "bounce") occurred so frequently that some of the rectifiers were no longer able to re-ignite and "locked-out".

During the running of the test train as many as 14 consecutive pantograph "bounces" were recorded at one place at speeds of 45 m.p.h. and over. This was in Clapton Tunnel where the clearance is restricted and there are changes in the support of the contact wire due in part to the severe reverse curvature. Frequent loss of contact was also recorded when passing through the Clapton neutral section where the overhead construction appears also to have upset the rhythm of the pantograph. At other places the "bounces" were much less frequent. Steps are now being taken to eliminate as far as possible these sources of trouble.

134. The General Electric Company is now fully engaged in applying the agreed modifications. This is no easy task because it involves alterations to the circuits of 71 traction motor equipments and 71 transformers, and the reconstruction of nearly 600 mercury arc rectifier cylinders, besides the provision of the additional safeguards already mentioned in this report. The work has to be done piece meal and will take time. Consequently it is unlikely that all the G.E.C. units will be completely modified before the end of the summer, especially in view of the transformer difficulties to which I now refer.

135. During trial running on the North East London lines investigations into the blowing of some tertiary fuses led to the discovery of a weakness in the transformer winding clamps. This was put right on all the transformers before the public electric services on steam timings were opened on these lines on 14th November.

Subsequently two transformers associated with train failures were examined by Mr. F. J. Lane, a partner of Messrs. Preece, Cardew and Rider who was appointed by the Commission to investigate transformer failures. He was satisfied that in the one case of internal damage the conditions were exceptional and that the two occurrences considered together did not justify doubts about the performance of the other G.E.C. transformers, pending the completion of the test programme mentioned in my first interim report.

136. However, as mentioned in paragraph 63, a transformer in Unit No. 519 failed in service on 28th April and as a result the whole question of transformer performance has been reviewed. The cause of the failure was traced to a breakdown between some of the turns in the secondary winding. There were also signs of turn displacement, and a short-circuit had occurred between two tap connections.

Examination of the other four transformers which had been returned to the Contractors' works revealed no significant winding movement in two of them, but slight displacement of some of the secondary turns in the other two. There was evidence in all of them of some movement of tap connections and in one case the insulation had been abraded sufficiently to cause a short-circuit. None of the primary windings was damaged or displaced and there were no other signs of electrical failure. The displacement of the turns in the secondary winding and the movement of tap connections indicated, however, that the transformers had been subjected to severe electro-magnetic forces.

A transformer which had not been in service was subjected to Mr. Lane's short-circuit test programme but this was not conclusive because of an error in the test plant connections. A further test will be carried out as soon as another transformer is available. The examination of the secondary winding revealed, however, some overriding of the turns of one coil, the displacement of turns in both coils and the movement of certain tap connections.

137. A meeting was held on 24th May between the British Transport Commission, the Consulting Engineers and the Contractors, at which I was present. After a full discussion of the factors affecting design and performance Mr. R. N. Millar, Managing Director of the Engineering Group of the General Electric Company, stated that, in his and his experts' opinion, the transformers had stood up well to the onerous treatment to which they had been subjected as a result of repeated backfiring of the rectifiers, and they thought that the breakdown of transformer No. 519 was exceptional and did not indicate a failure trend on account of weak winding. Mr. Millar agreed that the tap connections must be strengthened, but stated that his Company was satisfied that the transformers as designed were fit and safe to remain in service after this

modification and that they would have many years of reliable life, provided the rectifier troubles were overcome—his Company had no doubts about this. Nevertheless the Commission propose to carry out further tests on transformers before deciding whether more modifications are necessary.

138. It is satisfactory to report that good progress has been made with the modification of the Glasgow multiple-unit trains. The modified transformer has passed successfully the tests to which it was subjected by Mr. Lane, and large numbers of reconstructed trains have been undergoing trial running on the Glasgow suburban lines. Some troubles have been experienced as is to be expected after such extensive alterations, but none is fundamental and I have been assured by the Commission that all the minor defects which have come to light are being rectified.

139. A series of tests has been carried out under Mr. Lane's supervision with the object of confirming the cause of the failure of the Glasgow transformers and in particular to establish the effect of frequent changeover from one voltage to another. Tests have also been made to prove that the modifications which have been introduced will be satisfactory, and experience with the reconstructed train has confirmed their effectiveness. I hope, therefore, that before long a satisfactory public electric service will be resumed on the Glasgow suburban lines.

140. The investigations in the Eastern Region have shown that the failures have arisen primarily on account of the onerous conditions set up when running on the 6.25 kV section of the dual voltage system and they indicate the need for more research. I therefore recommend that this research be extended to cover all high voltage A.C. lines and to include the running of test trains similar to that in operation on the Eastern Region.

141. In the first place the problems that arise when changing over from one voltage to another requires further study ; secondly, the operation of the air-blast circuit-breaker should be examined to see whether the effect of rapid "chopping" can be reduced when operating on 6.25 kV.

142. Thirdly, it is desirable to examine further the causes of pantograph "bounce" which has been excessive in places. The relationship between the moving pantograph and the overhead wire depends not only on the alignment and level of the wire but also on the reaction of the vehicle, which is influenced by the alignment, level and cross-level of the track as well as by its own springing characteristics. Such reactions are accentuated by the speed. All these factors need to be considered and standards laid down to ensure that the loss of contact between the pantograph and the overhead conductor will be kept within reasonable limits.

143. Finally, these investigations have shown that faults in minor pieces of equipment and the premature operation of safety devices also may cause troubles which lead to breakdowns in service. The need for simplification is apparent and I recommend that this question be pursued vigorously.

144. In conclusion I record with appreciation the great co-operation I have received from all concerned in this Inquiry—from the Officers and Engineers of the British Transport Commission and the Scottish and Eastern Regions—from the Contractors, the General Electric Company and the Associated Electrical Industries—and from the Consulting Engineers. Mr. F. J. Lane has continued to give me much help and advice on all matters connected with transformer failures. Mr. E. L. E. Wheatcroft and Mr. T. W. Wilcox have

rendered me valuable assistance in the preparation of this report and my conclusions are based largely on the advice they have given me.

145. Attention has been concentrated on establishing the basic causes of the failures which disrupted some of the A.C. electric services and on effecting permanent cures. The main objective has been achieved, and although no system of railway traction can always be trouble free, I have every expectation that multiple-unit electric trains will in future give thoroughly efficient and satisfactory service.

A full report on all the factors affecting these failures and on other relevant matters will be presented later.

I have the honour to be,

Sir,

Your obedient Servant,

C. A. LANGLEY,

Brigadier.

The Secretary,
Ministry of Transport.